

# Detection of Small Kuiper Belt Objects by Stellar Occultations

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Knowledge of the Kuiper Belt is currently limited to those objects that can be detected directly. Objects with diameters less than  $\sim 10$ km reflect too little light to be detected. These smaller bodies could contain most of the mass in the Kuiper Belt while the abundance of these bodies may constrain the distribution of mass. The overall size distribution of bodies within the Kuiper Belt can also be inferred from the relative abundances of sub-km and larger bodies.

Stellar occultations are already used to study dark objects in the Solar System, such as asteroids or planetary rings. Occultation by a KBO of a size comparable to, or larger than, that of the Fresnel Scale will result in Fresnel diffraction. Detection of diffraction effects requires fast multiple-star photometry, which will be conducted in July 2007 using the Orthogonal Parallel Transfer Imaging Camera (OPTIC) mounted on the University of Hawaii 2.2m telescope on Mauna Kea. This paper details how knowledge of the mass and structure of the outer Solar System may be obtained through the detection of serendipitous stellar occultations.

## Introduction

The Kuiper Belt is the remnant of the proto-planetary disk from which the planets formed. Kuiper Belt Objects (KBOs) are some of the most primordial objects in the Solar System. The total mass, composition and spatial and size distributions of KBOs are indicators of conditions in the early Solar System, and the nature of subsequent processing of material. Current knowledge is limited to objects larger than  $\sim 10$ km that represent only a fraction of the total population.

Over 1000 trans-Neptunian objects have been discovered since 1992. An extrapolation of the size distribution observed for larger KBOs suggests the Kuiper Belt has a mass of  $0.1M_E$  [6]. The actual mass of the Kuiper Belt may be several times this value when the smallest KBOs are taken into account.

Stellar occultations provide an indirect method to constrain the abundance of small objects in the outer Solar System. The method consists of monitoring the flux from a suitable target star using fast photometry and identifying significant dips in flux. The method has been previously used to detect rings around the icy giant planets and to investigate planetary atmospheres (e.g. [5]). Bailey [1] first suggested that stellar occultations could detect small objects in the Solar System. In the last 5 years the necessary technology has become available to acquire rapid photometry. Reported observations to date have been sparse, with less than 100 possible detections reported [2, 11]. A larger sample is needed to reliably estimate the number of small ( $< 10$ km) KBOs.

Here I discuss the importance of using stellar occultations to detect km and sub-km sized bodies in the outer Solar System.

## Size Distributions within the Kuiper Belt

A power law can be used to describe the size distribution of objects in the Kuiper Belt:

$$N(r) = Cr^{-q}dr \quad (1)$$

Empirically, the parameter  $q$  is equal to 4 for observed KBOs with sizes greater than 10km [9]. Dynamical simulations suggest  $q \sim 3.5$  for objects smaller than 10km (e.g. [4]). The sizes of smaller bodies are primarily governed by collisional processes while sizes of larger objects are controlled by accretional processes as the gravitational influence of the bodies becomes important.

Jupiter Family Comets (JFCs) are probably the km-sized progeny of KBOs that were recently scattered into the inner Solar System. There is some evidence that the size distribution governing JFCs is similar to that governing the smaller KBOs [12], which would support the theory that JFCs originate from the Kuiper Belt.

Fig. 1 shows the size distribution over time as modeled by Kenyon & Luu (1999). The transition between size distributions occurs at a size of 10km.

Extrapolating the number of known KBOs of a given size results in an estimation of 70,000 objects with sizes greater than 100km [6]. A similar extrapolation for small objects, following a size distribution of  $q=3.5$ , indicates there may be several orders of magnitudes more objects with sizes 1km [10]. These numerous small objects could contain the majority of mass in the Kuiper Belt.

## Diffraction Effects

Occultation of a source by an object with sharp edges will result in diffraction effects if each point on a resulting wavefront is considered as the center of a secondary disturbance, giving rise to spherical wavelets. Interference between wavelets then causes the observed diffraction effects. The characteristic scale of the diffraction effects is defined as the Fresnel scale, given by:

$$F = \sqrt{(\lambda D/2)} \quad (2)$$

This is approximately the factor by which the width of the occultation dip is increased. Fresnel diffraction effects will become important when the size of the occulting KBO is comparable to, or larger than, that of the Fresnel scale. At 40AU, observing at 550nm, the Fresnel scale is 1.3km. The characteristic length,  $\rho$ , is defined as:

$$\rho = \frac{r}{F} \quad (3)$$

For an object much smaller than the Fresnel scale ( $\rho \ll 1$ ), the diffraction effects (Fig 2a) are of low amplitude and will be obscured by noise associated with the observations. For  $\rho \sim 1$ , diffraction fringes will be observed (Fig 2b) and increase the occultation shadow of the event. The central peak (Poisson's Peak) is observed when the occulting object is directly between the source and the observer. This effect occurs only for spherical objects with smooth edges; KBOs will not have such geometries. Figure 2c shows the lightcurve for an object much larger than the Fresnel scale ( $\rho \gg 1$ ). Diffraction fringes still occur. The lightcurves presented assume a smooth, spherical object passes in front of a monochromatic point source. An object with rough edges will cause irregular diffraction fringes. In some cases, these may be detected if the object is comparable in size to the Fresnel scale. The extent of diffraction is dependent on the wavelength observed and so, in reality, the multi-wavelength flux will cause the diffraction fringes to become smoothed. Using a filter reduces this effect.

## Using Stellar Occultations to Detect Small KBOs

The lightcurves illustrated assume the star behaves like a point source. In fact, the angular diameter of the star projected at the distance of the occulting object may be larger than the angular diameter of the object. This would result in smoothing of the diffraction pattern, making it harder to discern. Thus, it is necessary to choose target stars carefully, choosing those with small angular diameters whilst being bright enough for fast photometry. The angular size of a star projected at a given distance depends upon the spectral type and distance to the star. The absolute magnitude and radius of a star are determined by its mass. The relation between spectral type and mass for main sequence stars is used to estimate the intrinsic properties of a star. For a star of constant apparent magnitude, early type stars have small angular sizes making them favorable as target stars. A 12<sup>th</sup> magnitude O5V star has a projected angular size of  $3\mu\text{as}$  while an M5V star of the same magnitude will project a diameter of  $280\mu\text{as}$ .

In addition to being early type on the main sequence, the stars must be located near the ecliptic. The classical KBO population is concentrated within a few degrees of the ecliptic and so to maximize the occultation rate I will restrict my search to this region. Early type stars are typically found in the galactic plane, near their formation regions in the spiral arms, and so the optimal region to examine lies where the ecliptic crosses the galactic plane.

The duration of the occultation event is the ratio of the size of the diffraction shadow to the object's apparent velocity. When the target star is small compared to the occulting objects the diffraction shadow is 3 times the Fresnel scale [11]. The apparent velocity of a KBO with respect to the occulted star is:

$$v = v_E[\cos\omega - D^{-1/2}] \quad (4)$$

where  $v_E$  is Earth's velocity,  $\omega$  is the angle from opposition to the KBO and  $D$  is the distance (in AU) from Earth to the KBO. At opposition the KBO's velocity is greatest, the event duration is shortest but the occultation rate (number of KBOs passing in front of the star each night) is lowest. Thus, if the instrument used is sufficiently fast to detect dips in flux on the timescales of the event duration one should observe at opposition to maximize the number of events detected. The timescales for events are typically less than one second, so a readout frequency on the order of 10s of Hz is needed.

## The Observations

The Orthogonal Parallel Transfer Imaging Camera mounted on the University of Hawaii 2.2m telescope on Mauna Kea will be used to simultaneously monitor several stars. The instrument is designed for high-precision photometric observations and is capable of fast readout (up to 100Hz; [7]). The star will be positioned in one of four 'guiding regions' near an amplifier. Only a small designated region,  $\sim 30 \times 30$  pixels, encompassing the star will be read out. The time-varying flux from each star will be analyzed, looking for dips greater than  $3\sigma$ . Given the short exposure times, the target stars must be brighter than 12<sup>th</sup> magnitude.

By monitoring multiple stars simultaneously occultation events caused by nearby objects (e.g. birds, planes) can be easily identified and discarded. Using OPTIC, up to 4 stars can be monitored at a time, although the availability of suitable target stars may reduce this number when observing. At least two stars will be observed per pointing to protect against spurious occultations. Instrument noise is not expected to dominate the total noise in the observations. It is not necessary to measure the sky background as this does not vary on such short timescales, instead it adds a small, constant offset to the intensity level of the target star. Atmospheric scintillation is the most significant source of error for these observations. It will be possible to discount dips caused by scintillation through careful analysis of positive variations from the mean and computing the standard deviation of the reading. Only dips greater than  $3\sigma$  will be considered as possible occultation events. The identified lightcurves can then be more closely examined for diffraction fringes.

OPTIC has enhanced efficiency at red wavelengths, peaking at about 750nm. The target early type stars are generally blue, however, and most possible target stars only have reported B and V magnitudes, which are needed to estimate the star's projected radius at 40AU. Furthermore, diffraction patterns are smoothed and harder to detect at longer wavelengths. I choose therefore to observe using a V-band filter.

Roques & Moncuquet [10] estimate an occultation rate of a few occultations per night (8 hours) based on an extrapolation of the size distribution and the number of known objects of a given size. I expect to detect between a few to tens of events over the five nights of observing time. The detectability of events depends on the duration and the size of the occulting object. The shortest events will not be temporally resolved by OPTIC. Additionally, objects much smaller than the star's projected size at that distance will cause only a partial reduction in flux from the star, which may be obscured by noise. These observations will only be sensitive to objects larger than  $\sim 1$ km. Events lasting longer than a few seconds, caused by large KBOs, will cause the instrument to lose guiding. These events are very unlikely but set the upper size limit of detectable KBOs at  $\sim 40$ km.

## Summary

I have presented here the case for using stellar occultations as a method to detect small KBOs that are too faint to observe directly. The method requires rapid photometry ( $>10$ Hz) on multiple stars. The target stars should project a size comparable to, or smaller than, the Fresnel scale at 40AU and so early type main sequence stars will be observed.

The planned observations will be sensitive to objects smaller than 10km. Diffraction fringes will be observable if their amplitude is several times that of the typical variations caused by scintillation. This is likely to occur for objects similar in size, or larger than, the Fresnel scale, although scintillation will vary from night to night.

Reported occultation events indicate the potential for this method to increase knowledge of the mass and structure of the Kuiper Belt. The majority of mass in the outer Solar System could be contained in objects undetectable by direct methods. Further observations will lead to a larger, more statistically significant, sample of sub-km objects that would otherwise remain undetected.

## References

- [1] Bailey M.E. *Nature*, V. 259, pp. 290-291 (1976)
- [2] Chang H.-K., King S.-K., Liang J.-S., Wu P.-S., Lin L. C.-C., Chiu J.-L. *Nature*, V. 442, pp. 660-663 (2006)
- [3] Dauger D. E. *Computers in Physics*, V. 10, pp. 591 (1996)
- [4] Dohnanyi J. W. J. *Geophys. Res.*, V. 74, pp. 2531-2554 (1969)
- [5] Elliot J.L. *ARA&A*, V. 17, pp. 445 (1979)
- [6] Jewitt D., Luu J., Chen J. *AJ*, V. 112, pp. 1225 (1996)
- [7] Howell S.B., Everett M.E., Tonry J.L. Pickles A., Dain C. *PASP*, V. 115, 813, pp. 1340-1350 (2003)
- [8] Kenyon S. J., Luu J. X. *AJ*, V. 118, pp.1101-1119 (1999)
- [9] Luu J. X., Jewitt D. C. *ApJ*, V. 502, pp.L91-L94 (1998)
- [10] Roques F., Moncuquet M. *Icarus*, V. 147, pp. 530-544 (2000)
- [11] Roques F., Doressoundiram A., Dhillon V., et al. *AJ*, V. 132, pp. 819-822 (2006)
- [12] Tancredi G., Fernandez J. A., Rickman H., Licandro J. *Icarus*, V. 182, pp. 527-549 (2006)

**Figure 1.** Evolution of the size distribution for objects in the Kuiper Belt, assuming an initial protoplanetary disk with a mass of  $10M_E$ , modeled over 37Myr. The rollover between  $q=3.5$  and  $q=4$  is seen at  $r \sim 10$ km. The observations discussed here will be sensitive to objects below this critical radius [8].

**Figure 2.** Lightcurves for simulated occultations of a monochromatic point source by a smooth, spherical object normalized to the intensity of the target star. (a): An object much smaller than the Fresnel scale causes low amplitude diffraction fringes. (b): Fresnel diffraction is an important effect for objects with  $\rho \sim 1$ . (c): Occultation by a large object will result in total extinction of flux from the target star. Lightcurves simulated using Fresnel Diffraction Explorer (<http://daugerresearch.com>); for algorithm details see [3].

Figures are available on YSC home page ([http://ysc.kiev.ua/abs/proc14\\_17.pdf](http://ysc.kiev.ua/abs/proc14_17.pdf)).